

ARMY RESEARCH LABORATORY



A Numerical Method for Predicting Thermal Erosion in Gun Tubes

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ARL-TR-1156

July 1996

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE July 1996	3. REPORT TYPE AND DATES COVERED Final, September 1993 - December 1995	
4. TITLE AND SUBTITLE A Numerical Method for Predicting Thermal Erosion in Gun Tubes			5. FUNDING NUMBERS PR: 1L162618AH80	
6. AUTHOR(S) Paul Weinacht and Paul Conroy				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U. S. Army Research Laboratory ATTN: AMSRL-WT-PB Aberdeen Proving Ground, MD 21005-5066			8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TR-1156	
9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) A numerical model for predicting the thermal erosion on the in-bore surface of a gun tube due to high convective heating is presented. The model is based on a one-dimensional implicit numerical solution of the heat conduction equation with an ablation boundary condition. The ablation boundary condition models the heat transfer at the melt interface and allows the ablation rate of the surface to be predicted. The model has been validated against previous numerical and analytical results for related model problems. Application of the numerical model has been made to predict the erosion on the M256 cannon firing the M829A1 projectile. The predicted ablation rates are within the observed erosion rates for normal erosion on the M256 cannon. <div style="text-align: right;">DTIC QUALITY INSPECTED 3</div>				
14. SUBJECT TERMS Gun Tube Erosion, Heat Transfer			15. NUMBER OF PAGES 29	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT SAR	

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1. INTRODUCTION

The erosion of the metallic surface on the inside of the gun tube during the course of firing can detrimentally affect the performance and useful life of the gun tube. Gun tube erosion can be a complex phenomenon because there are many possible mechanisms that contribute to the erosion of the inner surface of the gun tube. One of the primary mechanisms stems from the heat load transferred from the propellant gases to the gun tube wall. If the heat load is large enough, melting of metal at the inner surface of the gun tube can result. The high velocity propellant gases provide a means of removing the melted material as it is formed. The process of melting and subsequent removal of the melted material is referred to as ablation. The ablation process as a potential erosion mechanism is the focus of the current numerical study.

Evidence exists from previous studies that ablation is a potential erosion mechanism. A recent study by Bundy, Gerber, and Bradley¹ examined the single-shot thermal response of the M256 cannon firing the M829A1 projectile. Their results showed that the chrome plating on the inner surface of the gun tube provided sufficient protection to the gun tube so that melting of the chrome or the base (underlying) metal would not occur as long as the chrome plating on the inner surface of the gun tube remained intact. Their results also indicated that if the chrome layer were removed (due to chipping or other mechanical means), the base metal would reach its melt temperature at certain locations along the gun tube. Because their numerical approach did not model the phase change of the metal, no predictions of the ablation rate could be obtained. The purpose of the current study is to examine the ablation of the base metal, given the chrome layer has been removed during the course of previous firings.

In order to examine the ablation that may occur during heating of the gun tube, a one-dimensional time-dependent heat conduction model has been developed and is presented here. The code uses a Crank-Nicolson implicit scheme to solve the governing equation, which is cast in generalized coordinate form. Prior to the onset of melting, heating of the inner surface of the gun tube is modeled using a convective heating boundary condition. Once the melt temperature at the inner surface of the gun tube is reached, an ablation boundary condition is applied. (Here, ablation occurs when the solid surface reaches the melt temperature, undergoes phase change to liquid, and the liquid phase is immediately removed by external forces such as shear from the gun gases.) Since the model is a one-dimensional model, only radial temperature variations are considered. Surface heat transfer coefficients and gas temperatures used as inputs to the calculation were computed externally from the heat transfer computation using an interior ballistics code. The computed heat transfer coefficients assume that the inner surface of the gun tube is smooth and do not include the local variations, which might be caused by erosion cratering. Further details on the governing equations and numerical techniques are discussed in the following sections.

The numerical technique was validated with previously published numerical and analytical results for a model ablation problem. The validated technique was then applied to examine the thermal performance and ablation phenomenon associated with the M256 cannon firing the M829A1 kinetic energy projectile. Predictions of the in-depth temperature

response of the gun tube as well as the ablation rate were made. Details of the validation and application are given in the results section.

2. GOVERNING EQUATIONS AND BOUNDARY CONDITIONS

The in-depth temperature response of the unablated (solid) material was modeled using the one-dimensional heat conduction equation shown in equation 1.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r^\beta} \frac{\partial}{\partial r} (r^\beta k \frac{\partial T}{\partial r}) \quad (1)$$

By setting $\beta = 0$ or $\beta = 1$, the planar or axisymmetric form of the governing equation can be obtained. In this form of the equation, the relevant material properties—the density (ρ), specific heat (c_p), and the conductivity (k)—may be variable (but continuous). Only constant material properties were considered in the results presented here.

At the inner surface of the gun tube, two separate boundary conditions were applied depending on whether or not melting of the surface material was occurring. If the surface temperature was less than the melt temperature, a convective heat transfer boundary condition (Newton's Law of Cooling) was applied. This boundary condition simply states that, at the inner surface of the gun tube, the energy loss from the gun gases due to convection is balanced by the energy gain into the gun tube by conduction.

$$h(T_g - T_{wall}) = -k \frac{\partial T}{\partial r} \quad (2)$$

The convective heat transfer from the gun gases can be represented by a convective heat transfer coefficient, h , and a driving potential, which is the difference between the surface temperature, T_{wall} , and the gas temperature, T_g . T_g (along with other additional interior ballistic parameters) was obtained using the the NOVA code². Using results from the NOVA code, h was obtained from the Veritay code^{3, 4} using the correlation of Stratford and Beavers⁵. Computations for the firing of the M829A1 kinetic energy projectile from the M256 cannon were performed prior to the heat conduction computation. T_{wall} was obtained by coupling the boundary condition to the heat conduction equation.

The variations of the convective heat transfer coefficient and the gas temperature with time at 0.70 m from the breech are shown in Figures 1 and 2, respectively. Both the convective heat transfer coefficient and the gas temperature show a rapid rise after shot passage (~ 3 ms). The convective heat transfer coefficient reaches a maximum about 2 ms after shot passage, followed by a rapid decrease as the firing cycle proceeds. The convective heat transfer coefficient and the gas temperature vary along the axial length of the gun tube with the highest levels of heat transfer occurring near the breech.

Once the inner surface of the gun tube reaches the melt temperature, melting of the surface material is assumed to occur. After fully melting (complete change of phase from

solid to liquid), the liquid metal is immediately removed by the shearing action of the gun gases. Because surface material is being removed during the ablation process, the surface location (or the ablation rate) becomes an additional unknown in the problem. During the ablation process, two boundary conditions are applied as shown in equations 3 and 4.

$$T_{wall} = T_{melt} \quad (3)$$

$$\rho L \frac{ds}{dt} = h(T_g - T_{wall}) - k \frac{\partial T}{\partial r} \quad (4)$$

The first boundary condition states that the temperature at the surface where the phase change is occurring is equal to the melt temperature. The melt temperature is assumed to be a known material property. The second boundary condition is obtained from an energy balance at the melt surface. In addition to the heat transfer due to conduction and convection, the additional energy required due to the change of phase from solid to liquid (latent heat of melting) is also included. This boundary condition allows the ablation rate of the solid material, $\frac{ds}{dt}$, to be computed, given that the latent heat of melting, L , is a known material property.

Several milliseconds after shot passage, the convective heat transfer that drives the thermal heating of the gun tube decreases, and the ablation ceases. The convective boundary condition is then applied as before the melting occurred with the temperature at the inner surface computed by coupling the heat conduction equation and the convective boundary condition. As implemented in the numerical algorithm, the completion of the melting process is detected when the ablation rate changes sign.

To compute the in-depth temperature response of the gun tube, an additional boundary condition is required at the outer surface of the gun tube. Here, a convective boundary condition can be applied:

$$h_{\infty}(T_{outer-wall} - T_{\infty}) = -k \frac{\partial T}{\partial r} \quad (5)$$

where $T_{outer-wall}$ is the temperature at the outer surface of the gun tube, h_{∞} is the convective heat transfer coefficient, and T_{∞} is the ambient temperature. Representative values for h_{∞} and T_{∞} can be found in Reference 1.

Because the ablation process occurs during the first several milliseconds of the firing process, the heat can only penetrate a fraction of the distance from the inner surface of the gun tube to the outer surface of the gun tube. In this case, it may not be necessary to model the radial temperature response of the entire gun tube. By locating the outer edge of the computational domain far enough away so that the temperature response is unchanged during the heating process, a smaller computational domain can be analyzed. In this case, one of two boundary conditions may be applied: a constant temperature boundary condition or an adiabatic wall boundary condition.

The appropriate depth of the computational domain can be estimated using a depth-of-penetration analysis.^{6, 7} The depth of penetration, δ , is the approximate distance that the heat would penetrate in a given time, t , and is a function of the thermal diffusivity of the material, α .

$$\delta = \sqrt{12\alpha t} \quad (6)$$

Using a factor of safety of 2 or 3 will place the outer boundary of the computational domain far enough from the inner surface of the gun tube so that the temperature at the outer boundary remains unaffected by the heating of the gun tube during the simulation.

3. COMPUTATIONAL APPROACH

The governing equations and boundary conditions are solved using an implicit finite-difference technique. Prior to the onset of melting, the governing equations and boundary conditions are linear, and solutions are obtained in a direct (noniterative) fashion. During the melting process, the equations become nonlinear because the dimensions of the computational domain are coupled with the ablation rate. An iterative approach is utilized during melting to appropriately address the nonlinearity.

Because the boundary of the computational domain moves during the ablation event, a transformed version of the governing equation is employed in the computational approach. This allows the equations to be solved in a fixed computational space even though the physical boundary is moving. A generalized transformation between the computational coordinate, ξ , and the physical coordinate, r , is utilized. The transformed equations are shown as follows:

$$\rho c_p \left\{ \frac{\partial T}{\partial t} + \xi_t \frac{\partial T}{\partial \xi} \right\} = \frac{1}{r^\beta \xi_r} \frac{\partial}{\partial \xi} (r^\beta k \xi_r \frac{\partial T}{\partial \xi}) \quad (7)$$

$$\xi_t = \frac{-r_t}{r_\xi} \equiv \frac{\frac{\partial r}{\partial t}}{\frac{\partial r}{\partial \xi}} \quad (8)$$

$$\xi_r = \frac{1}{r_\xi} \equiv \frac{1}{\frac{\partial r}{\partial \xi}} \quad (9)$$

In this form, the nonlinear nature of the governing equation produced by the moving boundary is evident because the metric terms, ξ_r and ξ_t , are not constant and are dependent on the ablation rate.

The equations are solved using a Crank-Nicolson finite-difference technique. The finite-difference form of the governing equations is shown in equation 10.

$$\begin{aligned} \frac{\rho_j^{N+1} c_{p_j}^{N+1} T_j^{N+1} - \rho_j^N c_{p_j}^N T_j^N}{\Delta t} = & -\theta \xi_t|_j^{N+1} \left(\frac{T_{j+1}^{N+1} - T_{j-1}^{N+1}}{\Delta \xi} \right) - (1 - \theta) \xi_t|_j^N \left(\frac{T_{j+1}^N - T_{j-1}^N}{\Delta \xi} \right) \\ + \theta \frac{\xi_r|_j^{N+1}}{(r_j^{N+1})^\beta} \left\{ (r_{j+\frac{1}{2}}^{N+1})^\beta k_{j+\frac{1}{2}}^{N+1} \xi_r|_{j+\frac{1}{2}}^{N+1} \left(\frac{T_{j+1}^{N+1} - T_j^{N+1}}{\Delta \xi^2} \right) - (r_{j-\frac{1}{2}}^{N+1})^\beta k_{j-\frac{1}{2}}^{N+1} \xi_r|_{j-\frac{1}{2}}^{N+1} \left(\frac{T_j^{N+1} - T_{j-1}^{N+1}}{\Delta \xi^2} \right) \right\} \\ + (1 - \theta) \frac{\xi_r|_j^N}{(r_j^N)^\beta} \left\{ (r_{j+\frac{1}{2}}^N)^\beta k_{j+\frac{1}{2}}^N \xi_r|_{j+\frac{1}{2}}^N \left(\frac{T_{j+1}^N - T_j^N}{\Delta \xi^2} \right) - (r_{j-\frac{1}{2}}^N)^\beta k_{j-\frac{1}{2}}^N \xi_r|_{j-\frac{1}{2}}^N \left(\frac{T_j^N - T_{j-1}^N}{\Delta \xi^2} \right) \right\} \quad (10) \end{aligned}$$

The superscripts N and $N + 1$ represent the previous and current time steps, while the subscripts $j - 1$ and $j + 1$ denote spacial grid node locations immediately adjacent to node j . Coefficients that are to be evaluated between spacial grid nodes $j - 1$ and j or j and $j + 1$ are indicated by the subscripts $j - \frac{1}{2}$ and $j + \frac{1}{2}$, respectively. The parameter θ allows for switching between fully explicit and fully implicit schemes. In the computational results presented here, the second-order accurate Crank-Nicolson scheme ($\theta = \frac{1}{2}$) was utilized.

Finite-difference forms of the boundary conditions were also used. The conduction terms were evaluated using a first-order one-sided differencing to obtain the temperature gradient at the inner surface of the gun tube.

When melting is ongoing and the grid is moving, the solution is iterated at each time step because the temperature, ablation rate, grid node locations, and the metric terms are coupled in a nonlinear fashion. At each time step, the location of the melt surface at the $N + 1$ time step is first estimated based on the ablation rate at the previous time step. The grid node locations (which are dependent on the melt surface location) and metric terms at the $N + 1$ time step are then computed, and the temperature field at the $N + 1$ time step can then be updated from the governing equation and boundary conditions. Based on the predicted temperature field, the ablation rate at the $N + 1$ time step is determined from a finite-difference form of equation 4. Using the updated ablation rate, a new iteration loop can be started, to again predict the temperature field and ablation rate at the $N + 1$ time step until both the temperature field and the ablation rate converge.

To resolve the large temperature gradients at the inner surface of the gun tube, clustering of the computational grid was performed using an exponential stretching function. The resulting grid has fine spacing at the inner surface of the gun tube and progressively larger spacing away from the wall. The grid stretching utilized here allowed the grid spacing between adjacent nodes to increase by no more than 10% because highly stretched grids are known to reduce numerical accuracy.

The depth of penetration analysis, discussed earlier, can also be applied to select the spacing of the computational grid at the inner wall of the gun tube. After selecting the time-step for the integration procedure, the grid spacing at the inner wall of the gun tube can be estimated by computing the depth of penetration after one time step. Numerical experiments indicated that the grid spacing at the wall should be less than 10% of the depth of penetration after one time step to avoid inaccuracies in the predicted temperature profile and ablation rate.

4. RESULTS

The numerical method has been validated using previous numerical and analytical approaches for model problems involving phase change. These results are presented in the next section. After validating the numerical approaches, application of the technique was made to examine the ablation phenomenon in the M256 cannon firing M829A1 kinetic energy projectiles. Presentation of these results follows the validation results.

4.1 Validation: Ablation of a Semi-Infinite Solid

Over the past several decades, numerous studies examining the phase change process have been made. Results from two of these studies have been used to validate the currently developed numerical method. Landau⁸ has made one-dimensional time-dependent numerical predictions of a melting solid using a technique similar to that utilized here. Landau considered the case of a semi-infinite solid subjected to a constant heat flux. Goodman⁹ considered similar problems using a heat-balance integral approach. The approach of Goodman utilizes an assumed form of the temperature profile to analytically determine the heat conduction and ablation process. While exact solutions are not typically obtained, the results are reasonably accurate and are of a simple form. One of the cases addressed by Goodman was the melting of a semi-infinite solid under constant heat flux. In both cases, an ablative boundary condition was utilized; that is, the liquid phase was immediately removed following melting.

The problem of the heating on a semi-infinite solid subjected to constant heat flux was also addressed using the current numerical method. A finite computational domain was actually utilized in the computation, though the unheated boundary was placed far enough from the heated boundary so that the temperature near the unheated boundary did not change during the computation. The solid initially had a uniform temperature distribution of T_o and a specified melt temperature, T_{melt} . The results are scaled by the time to melt, t_{melt} , which is a function of applied heat flux. The instantaneous location of the solid surface, $s(t)$, relative to the fixed coordinate, r , is shown schematically in Figure 3.

Figure 4 shows the predicted in-depth temperature profile at four different times during the ablation process. The results were obtained using material properties corresponding to gun steel (Table 1). In addition to the numerical results, the analytical results obtained using the heat-balance integral approach of Goodman are also shown at the onset of melting and during steady-state melting. The numerical solution and the analytical results differ by less than 0.2% at the onset of melting. (Though not shown both results also show similar agreement with the exact analytical solution.) As the melting progresses, the temperature gradient at the surface is reduced due to the additional energy required to melt the solid. After approximately eight times the time required to reach the melt temperature, the numerical results show that the temperature profile has nearly reached the steady-state temperature profile. The differences between the analytical and numerical steady-state temperature profile are less than 2% of the difference between the melt temperature and the initial temperature. Exact agreement between the two results is not expected because the assumed form of the temperature profile in the heat-balance integral approach is not an exact solution.

A comparison of the predicted ablation rate obtained using the current technique with the results of Landau is shown in Figure 5. The computed ablation rates are scaled by the steady-state ablation rate, which can be calculated analytically. The current results are generally within 1%–2% of the results of Landau for the three different sets of material properties, including properties close to gun steel. The largest difference between the two sets of results is 4%. (Differences between the results of Landau and the current result may be more related to problems in extracting the data from the original published graphs of Landau than to numerical accuracy.)

The results show that the ablation rate approaches the steady-state ablation rate in an asymptotic manner with materials having a larger value of m approaching the steady-state ablation rate at earlier nondimensional times. The predictions of the steady-state ablation rate were obtained by running the computation for extended time ($t > 15t_{melt} - 200t_{melt}$ depending on the material property m). The predicted values were within 0.1% of the exact analytical results presented by Landau.

4.2 Application to the M256 Cannon Firing an M829A1 Projectile

Application of the numerical technique for predicting gun tube erosion was made to the M256 gun tube firing an M829A1 projectile. The gun tube is fabricated with AISI 4340 steel with the properties shown in Table 1. The inner surface of the gun tube is coated with a thin chrome layer which protects the gun tube. The chrome has a higher melt temperature and hardness than the gun steel.

Preliminary computations demonstrated that with the chrome layer intact, both the chrome layer and the gun steel would not melt (or ablate) due to convective heating during a single shot firing cycle. However, if the chrome layer were removed, the inner surface of the gun tube could reach its melt temperature during the firing cycle at locations near the breech of the gun. This behavior has been noted previously¹. It has been noted that the chipping of the chrome layer can occur after several hundred firings. The results presented here address the erosion of the gun tube following the removal of the chrome layer.

Computations of the thermal response of the gun tube were made for a single-shot firing scenario with the initial gun tube temperature assumed to be 294 K. The propelling charge temperature was 294 K corresponding to ambient conditions. The thermal response of the gun tube was computed at several axial locations along the gun tube to demonstrate variation in the thermal response along the length of the gun tube.

The temperature response of the gun tube on its inner surface as a function of time is shown in Figure 6. Results at four different axial stations along the gun tube are shown. At 0.70 m and 0.76 m from the breech, the inner surface of the gun tube reaches the melt temperature, and some ablation of the inner surface occurs. Further down the bore of the gun tube, the convective heat transfer drops to a level where melting of the gun steel does not occur.

Since the ablation occurs over such a short duration, it appears to have little effect on the temperature response of the gun tube except during the time period when the ablation occurs. Figure 7 shows the temperature response of the gun tube at 0.70 m from the breech. Two computational results are shown: one with the ablation model and one with no ablation model. The results differ by less than 20 K immediately after the ablation is complete, with the difference decreasing to less than 5 K later in the firing cycle.

In other applications, such as thermal protection for spacecraft re-entry, the ablation process can provide a measure of thermal protection, in that a portion of the heat input into the solid is expended in the phase change of the material. However, due to the short duration of the ablation process in this application, the ablation does not have much effect

on the total heat input into the gun during a single-shot firing. For example, at 0.70 m from the breech, the difference in the total heat input to the gun tube during firing with or without the ablation model is less than 1%.

The ablation rate of the gun tube as a function of time at two locations near the breech is shown in Figure 8. The location 0.70 m from the breech shows a much higher rate of ablation than at 0.76 m from the breech. As shown in the previous figure, this location reaches the melt temperature first and remains at the melt temperature for a longer duration. The total ablation for a single firing was $1.97\text{ }\mu\text{m}$ and $0.31\text{ }\mu\text{m}$ at 0.70 m and 0.76 m from the breech, respectively. Over 400 firings, this ablation rate would translate to a total eroded depth of 0.8 mm and 0.12 mm at these two stations. The computed erosion depths are apparently the right order of magnitude for normal observed erosion¹.

The in-depth temperature profile during the ablation event, shown in Figure 9, demonstrates the limited depth of heat penetration since the beginning of the firing cycle. The results justify the use of a one-dimensional approach for examining the ablation event because the temperature profile should be influenced by the conditions immediately surrounding a given location. The results also imply that some types of active measures for removing the heat from the gun tube may be ineffective for preventing erosion unless they can affect the conditions very close to the gun tube wall.

Clearly, the use of multidimensional approaches would be required if the geometric effects resulting from gun tube rifling or erosion channels are to be investigated. The development of such approaches is seen as a desirable research objective.

Additional computational results were generated to quantify the sensitivity of the ablation process to the convective heating. The results showed that a 4% reduction in the convective heat transfer coefficient or a 2% reduction in the gun gas temperature is enough to eliminate the ablation at 0.70 m from the breech. This is one indicator of how sensitive the ablation event might be to effects that might augment or retard the heating at the in-bore surface. It also serves as a caution to the analyst who is modeling erosion because even though the bulk of the input heat may be provided by the convective heating, additional minor sources of heating may yield enough additional heat to contribute significantly to the total amount of erosion.

5. CONCLUSION

A numerical method for estimating the erosion that occurs within gun tubes due to high convective in-bore heating has been developed. The method has been successfully applied to estimate the erosion that may occur during the firing of M829A1 kinetic energy projectiles fired from the M256 cannon, the main gun on the M1 tank.

Numerical predictions have demonstrated that, with the chrome layer intact, melting or ablation of the chrome layer or the base gun steel is not expected to occur. However, the predictions show that if the chrome layer is removed (which has been observed after several hundred firings), erosion can occur within a region between the breech and 0.75 m down-bore of the breech. The predictions show that the erosion occurs over a very short duration

shortly after shot passage. The predicted levels of erosion are consistent with experimental observations.

During the course of the study, one significant technical issue emerged: the accurate prediction of erosion rates may be a challenging endeavor because the erosion occurs over a very short duration and the rate is quite sensitive to a number of factors. In this study, care was taken to ensure grid-independent solutions. Inaccuracies were demonstrated when inappropriate selection of grid parameters such as grid stretching and spacing was made. Other issues such as the accuracy of the predicted surface heat transfer were not investigated in this study but potentially have a significant effect on the predicted erosion rate. (Many other studies have addressed this issue, but typically these studies have focused on the total heat transfer to the gun tube, rather than the peak heat transfer that really drives the erosion.) While these may be issues for the physical modeler, this is actually beneficial for the ballistician because it means that subtle changes in the design can dramatically change the erosion characteristics of the gun tube/projectile system. The development of analysis tools for gun tube erosion can provide the designer with important information as to whether design changes improve or degrade the erosion characteristics of a particular design.

Table 1. Thermal Properties of Gun Steel

	Gun Steel	Chrome
c_p	469.05 J/kg-K	505.3 J/kg-K
k	38.07 J/(m-s-K)	83.75 J/(m-s-K)
ρ	7827. kg/m ³	7191. kg/m ³
L	270. kJ/kg	-
T_{melt}	1780. K	2130. K

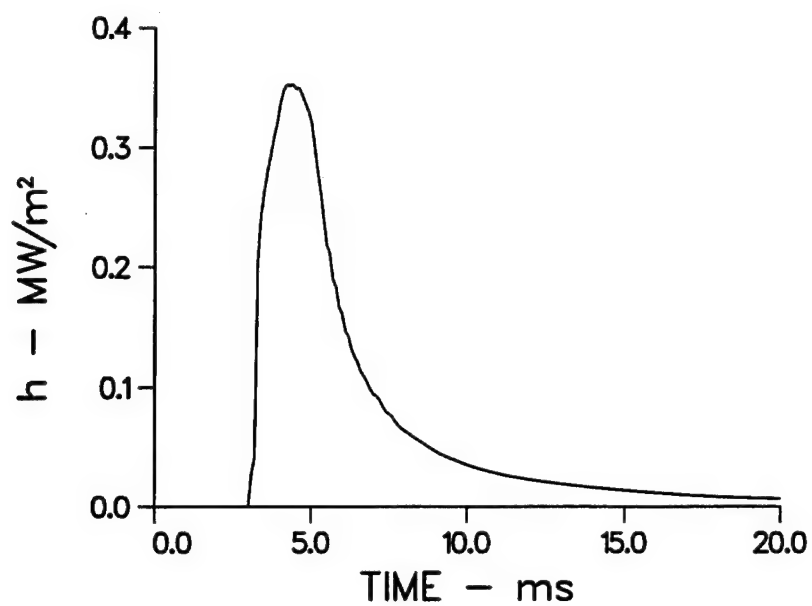


Figure 1. Predicted convective heat transfer coefficient versus time, 0.70 m from the breech, M256 cannon firing an M829A1 projectile.

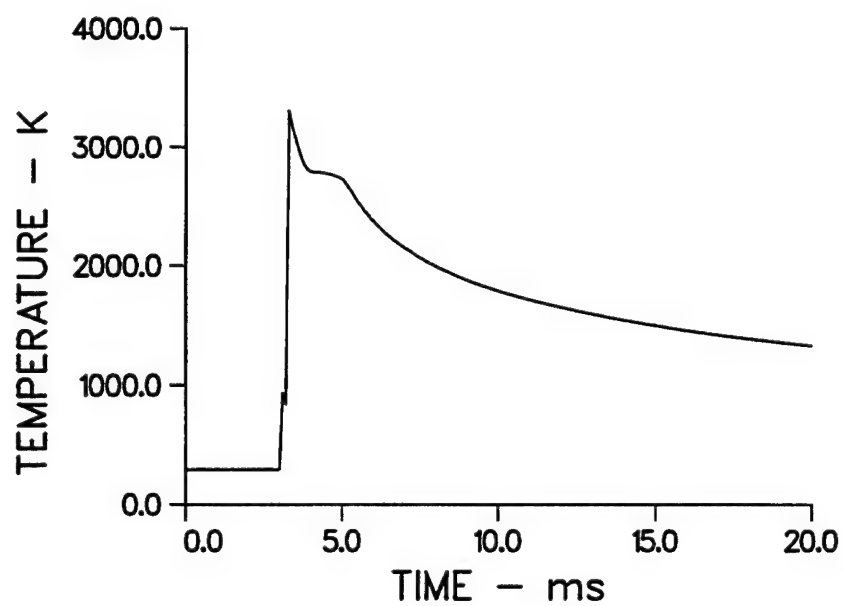


Figure 2. Predicted in-bore gas temperature versus time, 0.70 m from the breech, M256 cannon firing the M829A1 projectile.

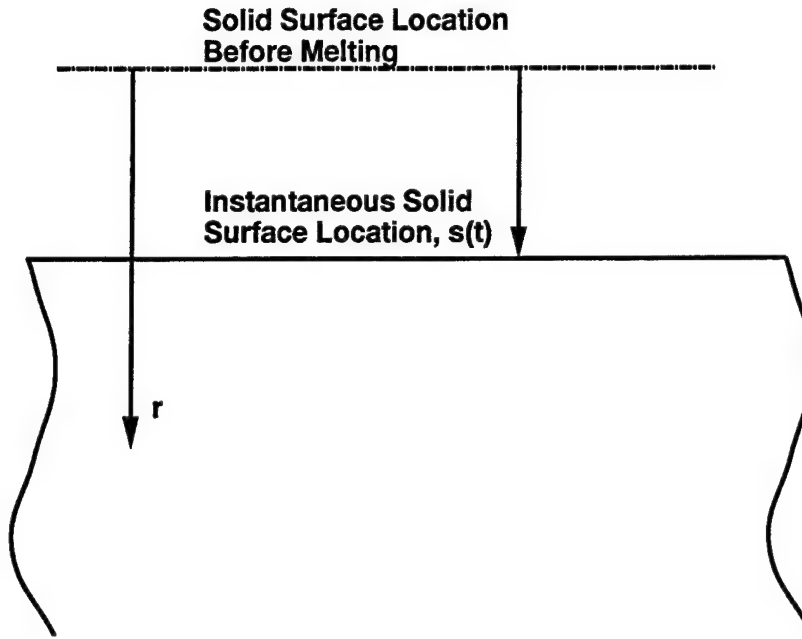


Figure 3. Schematic for ablation of a semi-infinite solid.

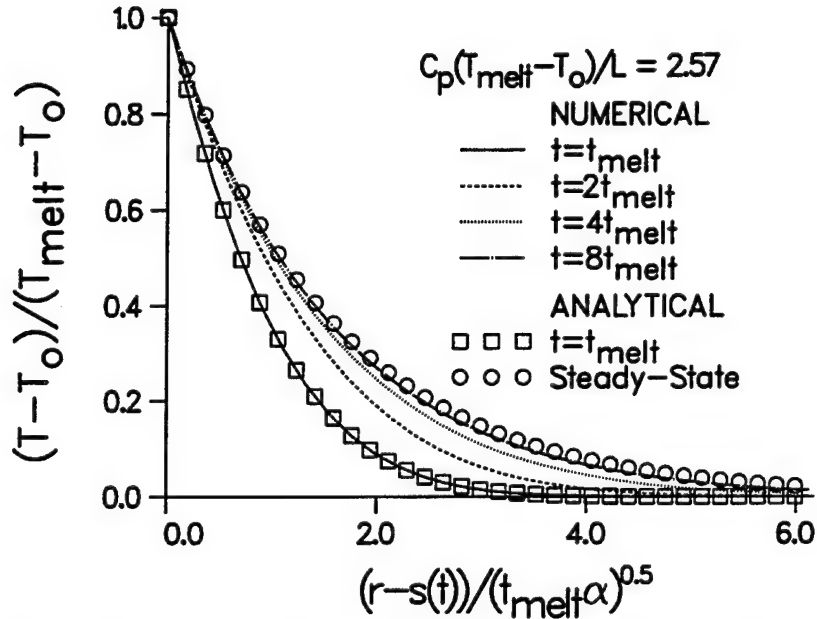


Figure 4. In-depth temperature profile during ablation process for a semi-infinite slab subject to constant rate heat flux.

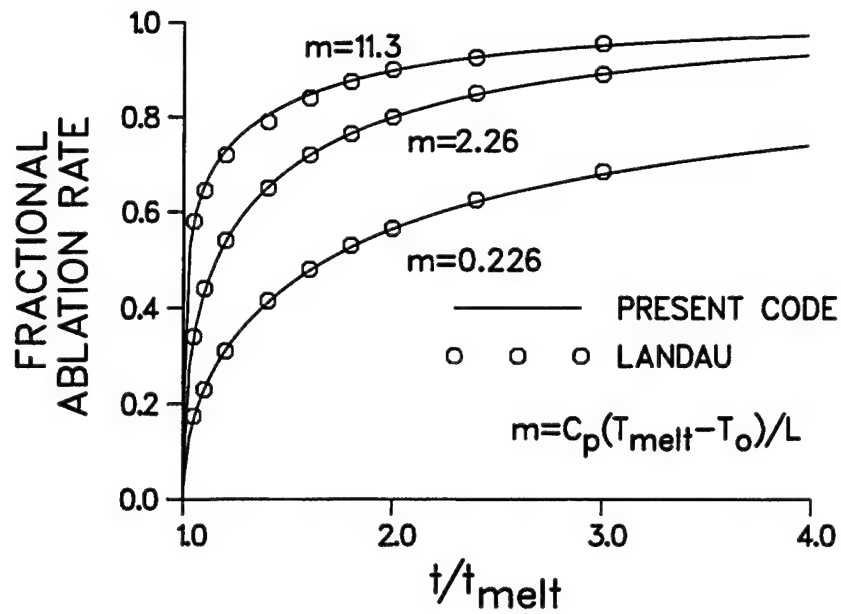


Figure 5. Fractional ablation rate versus time for a semi-infinite slab subject to constant rate heat flux.

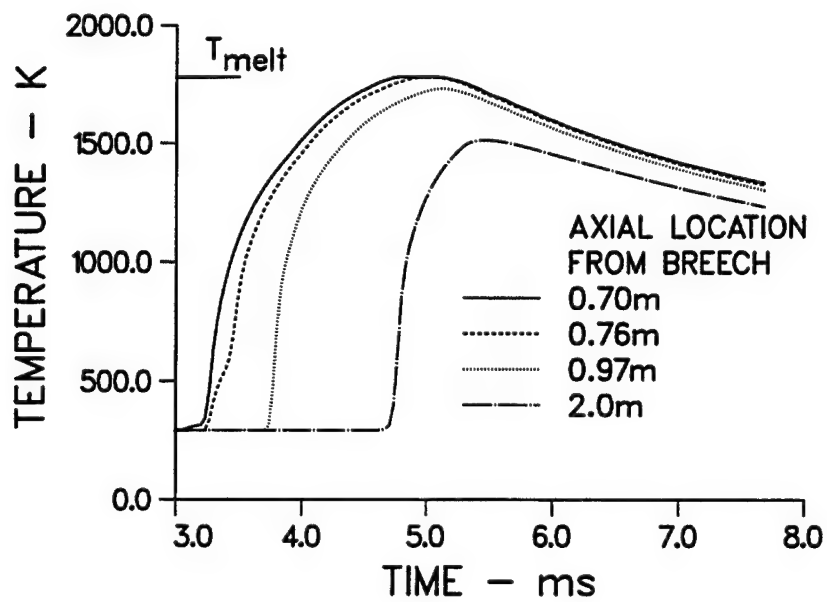


Figure 6. In-bore surface temperature of gun tube during firing cycle at various axial locations.

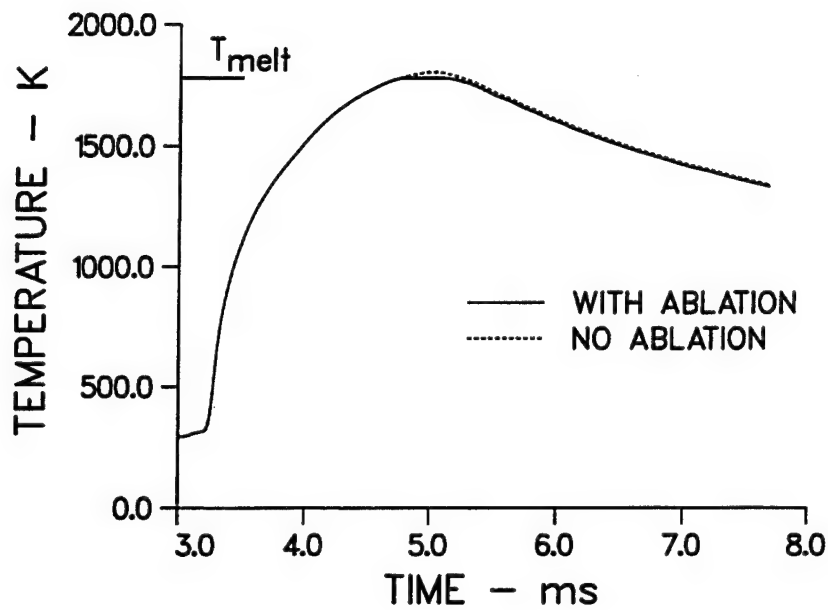


Figure 7. In-bore surface temperature of gun tube during firing cycle at 0.70 m from the breech, with and without ablation model.

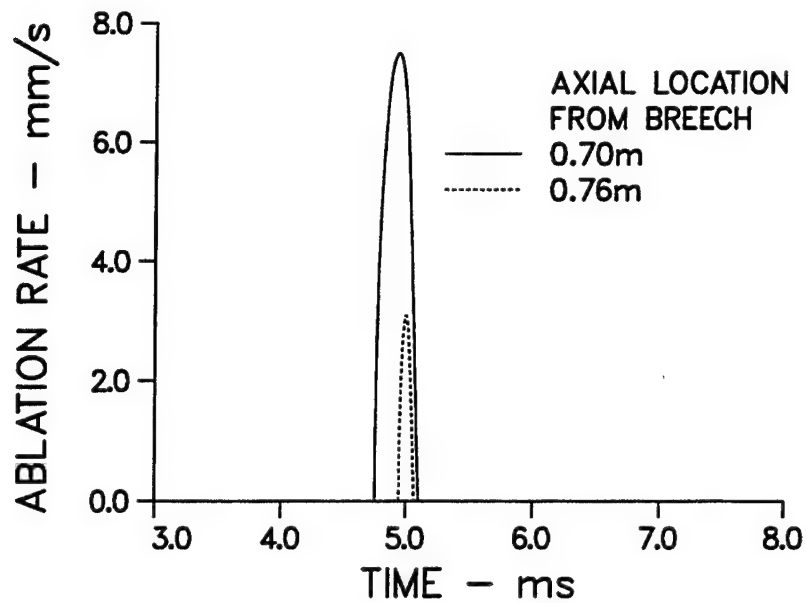


Figure 8. Ablation rate of in-bore surface of gun tube during firing cycle at two axial locations.

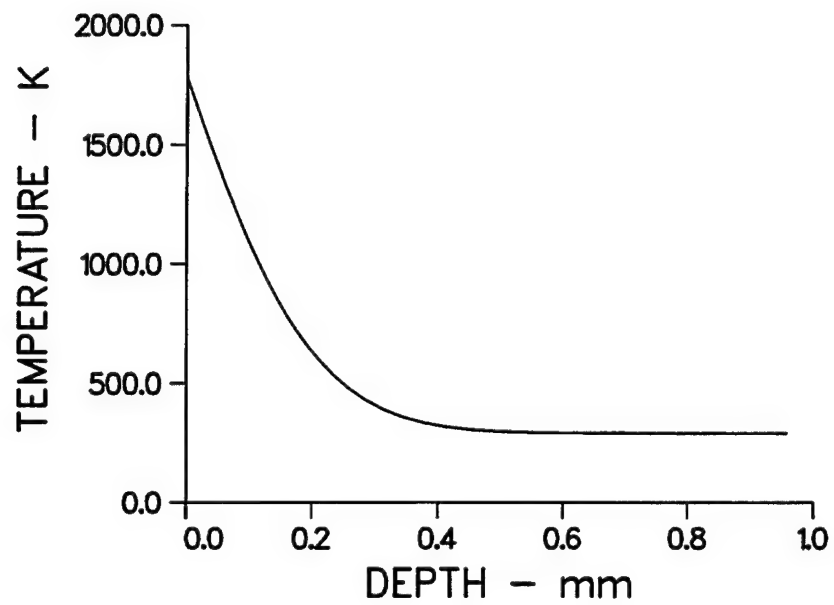


Figure 9. In-depth temperature profile of gun tube 0.70 m from breech during ablation process (5 ms).

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LIST OF SYMBOLS

c_p	specific heat
$\frac{ds}{dt}$	ablation rate
h	convective heat transfer coefficient
h_∞	convective heat transfer coefficient on exterior of gun tube
k	conductivity
L	latent heat of melting
m	heat capacity to latent heat ratio
r	radial coordinate
s	instantaneous location of solid surface
t	time
t_{melt}	time to melt
T	temperature
T_∞	ambient temperature
T_g	gas temperature
T_{melt}	melt temperature
T_o	initial temperature
T_{wall}	interior wall or surface temperature
$T_{outer-wall}$	external wall or surface temperature

Greek Symbols

α	thermal diffusivity
β	switch for planar ($\beta = 0$) or axisymmetric ($\beta = 1$) form of equations
δ	depth of heat penetration
θ	temporal differencing parameter
ξ	computational coordinate
ρ	density

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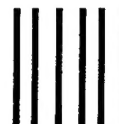
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